



# Detections of Warm-Hot Intergalactic Medium

L. Zappacosta<sup>1</sup>, R. Maiolino<sup>2</sup>, F. Mannucci<sup>3</sup>, R. Gilli<sup>2</sup>, A. Finoguenov<sup>4</sup>,  
A. Ferrara<sup>5</sup>

<sup>1</sup> Dipartimento di Astronomia e Scienza dello Spazio, Largo E. Fermi 2, I-50125 Firenze, Italy, [zappacos@arcetri.astro.it](mailto:zappacos@arcetri.astro.it)

<sup>2</sup> Osservatorio Astrofisico di Arcetri Largo E. Fermi 5, I-50125 Firenze, Italy

<sup>3</sup> Istituto di Radioastronomia - CNR Largo E. Fermi 5, I-50125 Firenze Italy

<sup>4</sup> Max-Planck-Institut für extraterrestrische Physik, Giessenbachstraße, 85740 Garching, Germany

<sup>5</sup> SISSA/International School for Advanced Studies Via Beirut, 4 34014 Trieste, Italy

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**Abstract.** Several popular cosmological models predict that most of the baryonic mass in the local universe is located in filamentary and sheet-like structures associated with groups and clusters of galaxies. This gas is expected to be gravitationally heated to  $\sim 10^6$  K and therefore emitting in the soft X-rays. We have investigated three fields with large scale structures of galaxies at redshifts 0.1, 0.45, 0.79 and found signatures of warm-hot thermal emission ( $kT < 1$  keV) correlated with the distribution of galaxies for the first two. The correlation and the properties of both X-ray and galaxy distribution strongly suggest that the diffuse X-ray flux is due to extragalactic emission by the Warm-Hot Intergalactic Medium (WHIM) predicted by cosmological models.

**Key words.** Large-scale structure of Universe – X-rays: diffuse background

## 1. Introduction

The baryonic census by Fukugita et al. (1998) clearly tells us that in the local universe we are still missing a significant fraction of baryons that are observed at high redshifts (Rauch et al., 1997; Burles & Tytler, 1998). Hydrodynamical models (Cen & Ostriker, 1999; Davé et al., 2001) identified a major reservoir of the missing baryonic matter (up to  $\sim 1/2 \Omega_b$ ) in a very diffuse gas phase with temper-

atures of the order of  $T \sim 10^5 \div 10^7$  K distributed in large scale filamentary structures connecting clusters of galaxies. The formation of these warm gaseous filaments is due to infall of baryonic matter into filaments of dark matter formed previously. The gravitational potential of the dark matter heats the gas through shocks and triggers the formation of galaxies. Such Warm-Hot Intergalactic Medium (WHIM) can be observed in the soft X-rays (up to  $\sim 1$  keV) as low surface brightness

structures. The detection of its radiation is hindered by the high Galactic foreground emission (Local Hot Bubble and Galactic halo), and extragalactic background contributions due to groups of galaxies, clusters and AGNs. Nonetheless, various detections have been claimed, obtained either by observing soft X-ray structures in coincidence of galaxy overdense regions or by detecting a soft X-ray excess from clusters of galaxies (Zappacosta et al., 2002; Kaastra et al., 2003; Finoguenov et al., 2003; Soltan et al., 1996). These observations have been possible by means of X-ray satellites very sensitive to low energies (< 1–2 keV), such as ROSAT and XMM.

Another successful method to detect the WHIM has been through the detection of absorption features of intervening medium in the spectra of background QSOs. The detectability of such absorption features does not depend on the brightness of the filaments but on their column density and on the brightness of the QSO in the background. So far WHIM has been detected through the absorption of high ionization oxygen and neon lines in the X-rays (e.g. Nicastro et al., 2002; Mathur et al., 2003) probing the hotter component, and in the far-UV (by means of FUSE and HST), probing the cooler component (see Tripp, 2002, for a review).

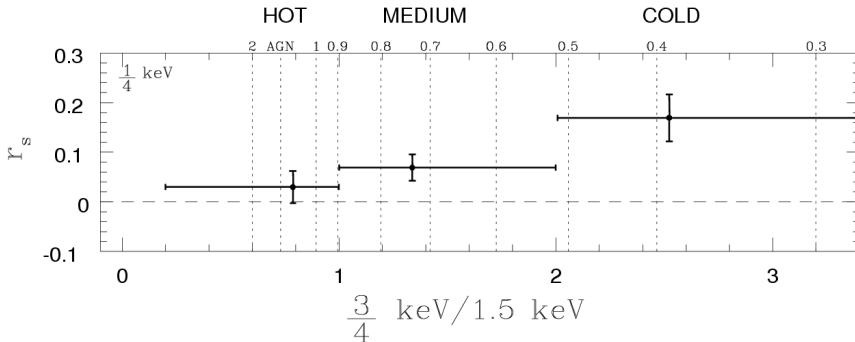
In this contribution we will show the analysis of three fields in regions with low Galactic hydrogen column density with candidate filaments up to redshift 0.8. In two of them we detected WHIM emission correlated with galaxy structures at low and intermediate redshifts (i.e. 0.1 and 0.45). In the third we did not find warm-hot thermal emission due to the optical superstructure at the highest redshift  $z = 0.79$ .

## 2. The low redshift field

The first field contains the core of the Sculptor supercluster. This region is crowded by more than ten Abell clusters and, for this reason, suitable for studies of

filamentary large scale structures connecting cluster members. This supercluster has already been studied with the purpose of detecting large scale X-ray diffuse emission by Spiekermann (1996) and Obayashi et al. (2000) with negative results.

In order to map the X-ray diffuse emission we retrieved from the ROSAT archive, and analysed (see Zappacosta et al., 2004), the 10 partially overlapping PSPC pointings inside the region. These data have been carefully reduced by the software described in Snowden et al. (1994) in order to allow an optimal analysis of low surface brightness structures. We have subtracted point sources both by using the SExtractor software (Bertin & Arnouts, 1996) and by means of a wavelet algorithm (Vikhlinin et al., 1998) taking into account for the radially variable ROSAT PSF (see Zappacosta et al., 2002, for more details). In order to compare X-ray data with the galaxy distribution we have used the Müster Redshift Survey Project (MRSP, Spiekermann et al., 1994) catalog selecting galaxies with magnitude  $r_F < 20.5$ . Most of the galaxies in this area for which the MRSP could determine the redshift are at the distance of the supercluster (Schuecker et al., 1989; Schuecker & Ott, 1991). A comparison between the distribution of galaxies and the X-ray ROSAT maps in the three bands centered at  $\frac{1}{4}$  keV,  $\frac{3}{4}$  keV and 1.5 keV (see Snowden et al., 1994, for their definitions) shows many diffuse structures in common. The X-ray structures could be the result of either true large scale gaseous emission or could arise from unresolved AGNs. In order to avoid the latter possibility we restricted the analysis to the two deepest maps (with exposures greater than 19 ksec) where we are confident that a larger fraction of the AGN contribution to the X-ray background has been resolved. Moreover we use the  $\frac{3}{4}$  keV/1.5 keV band ratio that is a temperature indicator to discern the WHIM soft thermal emission from the hard one of clusters of galaxies and the non thermal emission of AGNs.

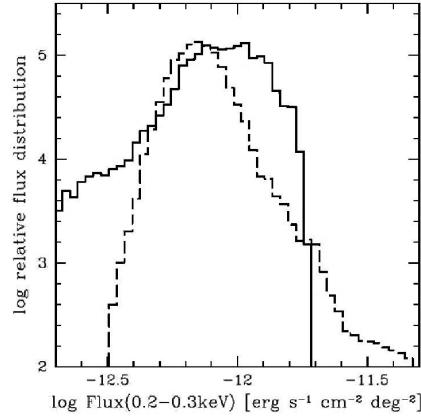


**Fig. 1.** Behaviour of galaxy/X-ray correlation for the  $\frac{1}{4}$  keV band. For each bin is showed the median value. Vertical dotted lines mark the corresponding temperatures labelled (in keV) at the top of the figure.

We have computed the Spearman's rank correlation coefficient  $r_s$  between the galaxy distribution and the X-ray flux and have found that it increases toward cold temperatures (see figure 1 for the  $\frac{1}{4}$  keV band). This behaviour is what we expect from a warm-hot gas correlated with the distribution of galaxies. The correlation in the softest ROSAT X-ray band for temperatures  $kT < 0.5$  keV is more than  $3\sigma$  significant. Moreover we have to mention that in a parallel program we have obtained a marginal detection of a deep OVII-K $\alpha$  absorption line at redshift of the supercluster in the RGS-XMM spectrum of a background quasar located in the vicinity (in projection) of the superstructure. This finding obtained through a short archival exposure (20 ksec) strengthen the evidence of the presence of a WHIM in the Sculptor supercluster.

### 3. The intermediate redshift field

In that field we have focused our attention on diffuse structures detected by Warwick et al. (1998) on several partially overlapping ROSAT PSPC pointings. In particular we have analysed the field centered at R.A.(J2000)  $10^{\text{h}}10^{\text{m}}14^{\text{s}}$  and DEC.(J2000)  $+51^{\circ}45'00''$ , obtained with an integration of 20 ksec. Our aims were



**Fig. 2.** Flux distributions for the ROSAT map (solid line) and X-ray sky simulation (dashed line) by Croft et al. (2001).

to detect again these structures measuring their physical properties and looking for galaxy structures coincident with them. Unlike the Sculptor supercluster region we do not know the spatial distribution of galaxies in this field. For this reason we have observed the field with the Wide Field Camera (WFC) at the Isaac Newton Telescope in service mode on 23 May 2000 and on 15 March 2001 in five broad band

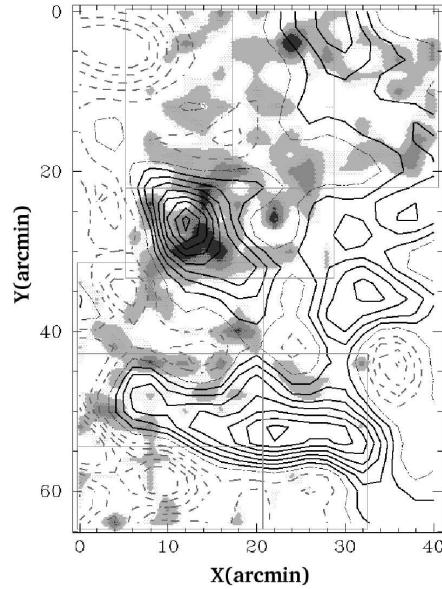
filters in order to obtain the photometric redshift estimates by means of the Hyperz code (Bolzonella et al., 2000) of the galaxies selected by SExtractor (see Zappacosta et al., 2002, for details).

For what concerns the X-ray maps reduction we have applied the same algorithms used in the previous field and finally corrected them for the HI absorption.

The detected structures are similar to those found by Warwick et al. (1998). Moreover we have compared the flux distribution in our map with the emission of X-ray sky maps simulated by Croft et al. (2001) in the energy range 0.2–0.3 keV (see fig. 2). We have found that the flux distribution in our field is in good agreement with the simulations.

In figure 3 is reported the comparison between the  $\frac{1}{4}$  keV band flux (contours) and projected galaxy distribution (grey scale) at redshift  $z_{\text{ph}} = 0.45 \pm 0.15$ . The main X-ray peak is coincident with the main structure in galaxies. The probability of a random coincidence of the two maxima is  $< 1\%$ . We have measured the spectral shape of the X-ray structures using the fluxes in the three X-ray ROSAT bands mentioned in the previous section. It can be modelled only by a thermal emission due to WHIM at temperature  $kT \sim 0.3$  keV. Moreover we have calculated that the density of emitting warm-hot gas corresponds to  $8 \times 10^{-6} \text{ cm}^{-3}$ . This estimate is in good agreement with the cosmological simulations that predict that at this redshift a WHIM should have a density of  $\sim 3 \times 10^{-6} \text{ cm}^{-3}$  while gas in groups of galaxies should be two order of magnitude denser.

In conclusion we have found an X-ray large scale structure with 0.2–0.3 keV flux, spectral shape and density in agreement with the predictions of cosmological simulations for the warm-hot baryonic gas at low redshift. Moreover this structure is coincident with an overdense region of galaxies at redshift  $z \sim 0.45$ . These evidences strongly



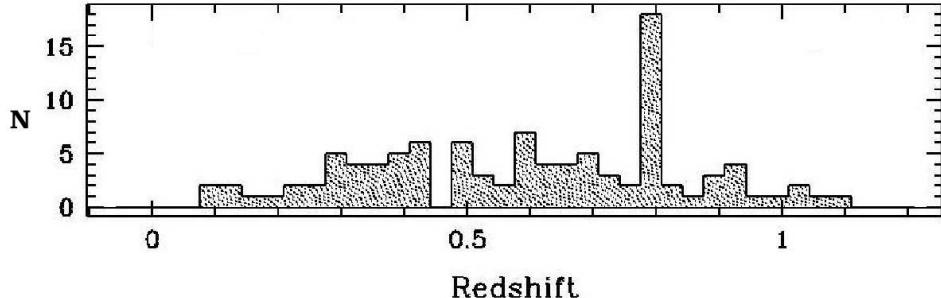
**Fig. 3.** The projected density of galaxies (grey scale) over the central region of the  $\frac{1}{4}$  keV ROSAT field (Zappacosta et al., 2002). The grey areas indicate overdense galaxy regions. The thin dot-dashed contour delineate the mean X-ray emission while thick solid and thick dashed ones regions with higher and lower X-ray flux. The thin solid grey lines show the pattern of the wide field ccd array.

support the idea that we have detected the emission of a WHIM at redshift  $z \sim 0.45$ .

#### 4. The high redshift field

The last field is a region in the Lockman Hole where 8 quasars with  $z = 0.79 \pm 0.01$  are present in a few Mpc. Due to this hint of large scale structure we have started a spectroscopic survey to investigate more carefully if it is really a superstructure.

We observed with DOLORES (Device Optimized for the LOw RESolution) at the Telescopio Nazionale Galileo (TNG) between the 26th of February and the 1st of March 2003. We used custom masks for



**Fig. 4.** The redshift histogram for the 104 galaxies with measured spectroscopic redshifts in the Lockman Hole.

multiobjects spectroscopy, each one with a field of view of  $9.4' \times 9.4'$ , mapping a region of  $\sim 324 \text{ arcmin}^2$ . We obtained low resolution spectra ( $\sim 11 \text{ \AA}/\text{px}$ ) for at least 200 objects over the  $\sim 4000$  galaxies detected with SExtractor in the preimaging session. The details of the observation and the data reduction and analysis will be reported in a forthcoming paper (Zappacosta et al., in prep.). We could measure redshifts for only 50% of objects. However we have found 18 objects at the redshifts of the archival quasars. Figure 4 show the redshift distribution of the objects. The sharp peak undoubtedly confirms the presence of a superstructure at redshift  $z \sim 0.79$ . These galaxies spans the whole region observed by us. That means that the whole structure has a projected size of at least 6 Mpc. In this case, similarly to the Sculptor supercluster field, we have tried to look for the X-ray emission of WHIM starting from the knowledge of the optical superstructure. However detecting WHIM at high redshift is an hard task because in this case the gas would have the bulk of its emission at energies lower than those we are probing with ROSAT. That means that we have to measure the low flux coming from the hard tail of its thermal emission.

We have analysed a deep ROSAT PSPC pointing (i.e. 65 ksec) and a 35 ksec XMM

map in about the same energy range (respectively 0.15–0.3 keV and 0.2–0.4 keV). The  $\frac{1}{4}$  keV ROSAT map show the presence of a diffuse X-ray structure coincident with the superstructure region. Using the other two ROSAT energy bands mentioned above we have found that its spectral shape is consistent with emission from unresolved AGNs (maybe active galaxies belonging to the superstructure). Actually the XMM map does not show any diffuse structure showing only point sources. However XMM maps in this energy range are still more difficult to process than the higher energy maps due to lots of spurious contributions such as the electronic detector noise. Maybe a future more accurate analysis and the addition of other XMM exposures will be useful to enhance the signal to noise and detect lower fluxes to constrain the presence of a warm–hot baryonic medium pervading the superstructure.

## 5. Conclusion

We have analysed three fields with low Galactic hydrogen column density in which we have found galaxy large scale structures at redshifts 0.1, 0.45, 0.79. In order to detect the local (i.e.  $z < 1$ ) warm–hot baryonic gas (WHIM) predicted nowadays by the cosmological simulations we have analysed them with ROSAT PSPC archival

pointings. For the two lowest redshift fields we have found WHIM correlated with the galaxy superstructures and with properties in good agreement with the simulations. For the farthest field we do not detect thermal emission by warm gas even using a 35 ksec XMM pointing (in the softest band). This is qualitatively consistent with the properties of the high redshift WHIM that can emits the bulk of its emission at energies lower than what the current satellites can explore (i.e.  $< 0.1$  keV).

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